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Functionality development of product innovation: An empirical analysis of the technological trajectories of smartphone

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Abstract. The purpose of this study is to analyze the driving technical characteristics in product innovation to predict technological trajectories. The analysis is based on hedonic price method and other approaches using empirical data of smartphone technology (*N*=738 models over 2008-2018). Results show technological trajectories supporting the evolution of smartphone technology. In particular, critical characteristics of technological evolution in smartphone technology are: RAM in Gb, 1[st] and 2[nd] camera in Mpx, memory in Gb and resolution in total pixels. Implications of innovation product management are discussed.
Keywords. Evolution of technology, Functionality development, Technological innovation, Product innovation management, Mobile phone, Smartphone, Technological change, Hedonic price regression, Economics of technical change.
JEL. O30, O31, O32, O33, O38.

1. Introduction

In the research field of technical change and technological forecasting, the analysis of technological advances is a central and enduring research theme to explain the evolution of technology and technological progress in society (Coccia, 2005, 2005a; Saviotti, 1985)[i]. In particular, the technology analysis of nature and evolution of innovation is important research field for predicting evolutionary pathways and critical characteristics of new technologies (cf., Arthur, 2009; Arthur & Polak, 2006; Hall & Jaffe, 2018; Linstone, 2004; Coccia, 2017). Scholars in these research topics endeavor of measuring technological advances, the level of technological development and changes in technology with different approaches directed to technological forecasting of emerging trajectories (Coccia, 2005; Daim *et al.,* 2018; Faust, 1990; Farrell, 1993; Sahal, 1981; Tran & Daim, 2008; Wang *et al.,* 2016). However, studies about methods for detecting the technical characteristics supporting the evolution of specific technologies are rather elusive. In this context, the study of technological advances in smartphone technology plays a vital role to explain general properties of the evolution of technology because this device is one of the most important Information and Communication Technologies (ICTs) used by people in society (Lee & Lim, 2014; Coccia, 2017a; cf., Teece *et al.,* 1997). The goal of this study is to suggest a method for technology analysis to detect and forecast the most important technical characteristics that support greater functionality development of smartphone technology in markets. Especially, the evolution of smartphone technology is modeled here in simple way with a linear function of hedonic pricing to detect technical characteristics of these ICTs that matter most. This approach can be generalized to analyze and explain evolutionary pathways of new technology in society. In addition, results can support best

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practices of management of technology for guiding funding for R&D and forecasting critical technologies and/or technical characteristics of products that are likeliest to evolve rapidly in society. Before presenting the method and results of this study, next section introduces the theoretical framework.

2. Theoretical framework

A smartphone or pocket-sized computer for voice, message and data communication is among the most important ICTs used by people worldwide in current society (Woods, 2018). The diffusion of mobile phones and smartphones, measured with subscribers, has growth rates higher than fixed phone (Watanabe *et al.,* 2012). Lee & Lim (2014, pp.808-809) argue that the main characteristics of mobile phones are: the mass in grams, physical dimensions in terms of length, width and thickness in mm, the measured dominant frequency of vibration in Hz, the peak acceleration measured in m/s^2 and peak inertia force measured in kg m/s^2, etc.

The evolution of smartphone technology is associated with stepwise functionality development ("the ability to dramatically improve performance of production processes, goods and services by means of innovation", Watanabe *et al.,* 2009, p.738). Watanabe *et al.* (2009, p.738) also argue that: "functionality development stimulates customer's demand leading to rapid increase in number of subscribers. This increase leads to dramatic decline in handsets prices as a result of both effects of learning and economies of scale. Balance between prices increase by functionality development and their decrease by effects of learning and economies of scale has been the driving force behind the growth in mobile phones" (cf., Lacohée *et al.,* 2003). In economics of innovation and industrial organization, scholars have investigated specific technologies, such as digital camera considering a relation between sales and characteristics of all camera models (Carranza, 2010). In particular, Carranza (2010, p. 605) argues that the functionality development of the quality of cameras is due to increasing resolution from around 0.5 in 1998 to more than 1.5 megapixels in 2001, whereas the average optical zoom of sold cameras has decreased slightly during the same period of time. This technological trade-off is explained as follows: increased resolution, which facilitates the use of a digital zoom, is a good and cheaper substitute for the optical zoom, especially among lower-quality cameras. In this context, Watanabe *et al.,* (2012) argue that learning effects in ICTs can be the sources of its self-propagating development of technology, acquiring new functionality from digital industry.

Stimulated by these studies, a fundamental problem in economics of innovation is which technological characteristics matter most in evolutionary pathways of new technology to predict fruitful technological trajectories (Coccia, 2005, 2005a, 2017). The literature of appropriate methods to explain this technological problem is rather scarce. The study confronts this question here by developing a theoretical framework based on technology as a complex systems and a hedonic pricing method, which endeavor to analyze smartphone technology to detect the most important technical characteristics driving evolutionary pathways over time.

Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a nonsimple way…. complexity frequently takes the form of hierarchy, and ….a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.,* (2011, p.9008) argue that: "The technology can be decomposed into n components, each of which interacts with a cluster of d–1 other components" (cf., Gherardi & Rotondo, 2016). Technology here is defined as a complex system that is composed of more than one component and a relationship that holds between each component and at least one other element in the system. Sahal (1981) points out that systems innovations are due to integration of two or more symbiotic technologies.

The analysis of technological advances has been performed with different approaches in engineering, scientometrics, technometrics, economics of innovation and related disciplines (Coccia, 2005, 2005a, p.948ff). One of these methods is the hedonic approach applied to technology analysis. Hedonic methods consider both economic and technical information (Saviotti, 1985). In economics, this approach is motivated by economic goals (e.g., sources of the competitive advantage of firms), whereas in engineering focuses on specific technical changes to improve performance of new products (Triplett, 1985, 2006). The assumption of this approach is a positive relationship between market price of a good and its quality. In particular, a product can be represented by a set of characteristics and by their value. The quality of the product Q_j is assumed to be a function of the defining characteristics as follows:

$$Q_j = f(a_1,...,a_i,...,a_n, X_{1j},..., X_{2j},..., X_{hj})$$

a_i = relative importance of the i-th characteristics (i=1, …, n)
X_{ij} =the qualitative level of the same characteristics in product j
Technological progress or technological evolution of the product j is given by the change in quality during a period of time:

$$TC_j = TP_j = \frac{\Delta Q_j}{\Delta t}$$

The observed changes in the price of a product can be decomposed into a "quality/technological change" effect and "pure price effect" (cf., Coccia, 2005a, pp.948-949; Saviotti, 1985, p.309ff). In general, Saviotti (1985, p.315, original emphasis) argues that: "hedonic price method has been applied mostly to products. In order to apply the method to process technology, one must be able to represent individual elements of the process and the process as a whole as sets of characteristics, and cost/prices must be known for individual elements of the process. Furthermore, a sufficiently large number of 'process models' should be available to obtain statistically significant results".

The hedonic pricing method is based on specific steps to assess the evolution of technology.

Firstly, in order to analyze technological evolution of a product, it is important to detect the product characteristics (X_{ij}) and their relative importance (a_i). Product characteristics can be found in the technical literature that provides the technical characteristics of products (i.e., those characteristics describing internal aspects of technology). Technical characteristics are manipulated by engineers in order to support innovative devices over time. Saviotti (1985, p.310) shows the example of the bore, stroke, number of revolutions per minute (RPM) of a motor car engine that are manipulated to supply the required engine power, fuel consumption, etc. Carranza (2010) has showed with a hedonic price model that camera prices decreased over time, controlling for the improving quality, measured with technical characteristics of resolution and digital zoom. This approach is important in markets because adopters of a technology are interested to technical characteristics supplied by a product to fulfil their needs.

Secondly, method of hedonic pricing requires the selection of a set of variables given by technical characteristics of a product.

Thirdly, the evolution of technology, after the identification of technical characteristics of a given product, is analyzed with a functional form for the relationship between quality and product characteristics. This functional form has to show that positive increments in technical characteristics levels must lead to an increase in quality. The simplest form of functional relationships between quality and product characteristics is a linear combination. However, the relationship between price and technical characteristics of a product is not necessarily linear, it can be semilog or log-log function (cf., Triplett, 1985). The choice between different functional forms of the hedonic pricing relationship is essentially an empirical problem (cf., Saviotti, 1985). In a log-log model of hedonic pricing, product prices are regressed with respect to technical characteristics, according to following equation:

$$logP_j = \alpha_0 + \alpha_1 logX_{1t} + \cdots + \alpha_i logX_{it} + \cdots + \alpha_n logX_{nt}$$

where
P_j= price of a product over time. It represents the value that firm has given to a specific product
X_i=explanatory variables are given by technical characteristics of product over time, such as weight, efficiency, velocity, etc.
a_0= constant
a_i= coefficient of regression (*i=1, …, n*)
This approach can explain the functionality development dynamism of technology for detecting technological trajectories directed to achieve and sustain competitive advantage of firms in markets with rapid change and fulfill needs of adopters. Next section presents the methods and materials applied here to analyze the evolution of smartphone technology.

3. Materials and method

This study focuses on functionality development of smartphone technology. The crux of the study here is the measurement of the evolution of technology. A brief background of the concept of evolution is useful to clarify this study. Evolution is the stepwise and comprehensive development [it derives from Latin *evolution –onis,* der. of *evolvĕre* = act of carrying out (the papyrus)]. In particular, the evolution of technology is due to major innovations, made possible by numerous minor innovations (Sahal, 1981, p.37). The process of development of technology generates the formation of a complex system (cf., Sahal, 1981, p.33). Sahal (1981) argues that: "evolution…pertains to the verystructure and function of the object (p.64)….involves a process of equilibrium governed by the internal dynamics of the object system (p.69)". Moreover, the short-term evolution of technology is due to changes within the system, whereas the long-term evolution is possible by forming an integrated system, the formation of increasingly comprehensive systems (Sahal, 1981, pp.73-74). In general, "the evolution of a technology often proceeds along more than one pathway so as to meet the requirements of its task environment" (Sahal, 1981, p.116). In short, evolution of technology is a constant process based on different technical and socioeconomic factors that generate a stepwise transition of technology from simple to a complex system. Using a Generalized Darwinism perspective (Hodgson & Knudsen, 2006, 2008), the evolution of technology, with the principle of selection of fruitful technical and economic characteristics, ensures diffusion and survival of successful technologies in markets (environment of technology).

The approach is modelled with a function of hedonic pricing to detect technical characteristics that matter most in evolutionary pathways over time.

4. Data and their sources

Smartphone is one of the most important ICTs used by people worldwide. The market of smartphone is concentrated at the brand level, with a small number of firms having a disproportionately large market share, creating an oligopoly (Lee & Lim, 2014). Sources of data here are originally sourced from trade literature (Punto & Cellulare, 2018). In particular, this study considers a sample of *N*=738 models of smartphone from 2008 to 2018 sold in Italy during the years 2012 and 2018 by famous brands: Apple. ASUS, HTC, Huawei, LG Electronics, Motorola, Nokia, Samsung, Sony, ZTE. Table 1 shows, in detail, the composition of the sample per brands of smartphone under study.

Table 1. *Sample of this study*

Brand of smartphone	N
APPLE	16
ASUS	46
HTC	81
Huawei	121
LG	64
MOTOROLA	61
NOOKIA	112
SAMSUNG	105
SONY	80
ZTE	52
Total cases (sample)	738

4.1. Measures

Firstly, this approach considers the monetary value of smartphones, which is expressed with the utilitarian unit of price in markets:

– Price *P* of smartphones (current Euros) sold in Italy during the years 2012 and 2018, though some models are launched in previous years.

Secondly, the evolution of technology here is measured with Functional Measures of Technological characteristics (FMT) in smartphone technology over 2008-2018 period to take into account both major and minor innovations (cf., Sahal, 1981, pp.27-29). FMTs in smartphone used here are given by:

- Display in inches
- Display resolution in total pixels[ii]= display size row × display size column
- Main Camera (megapixel, Mpx)
- Second Camera (megapixel, Mpx)
- Processor GHz (Giga Hertz, GHz)
- Memory Gb (Giga byte, Gb)
- RAM Gb
- Battery (milliampere hour, mAh).

4.2. Models and data analysis procedure

The technical characteristics of smartphone have accelerated from 2006 in line with the market of ICTs (cf., Lee & Lim, 2014). In order to detect the technological trajectories of the evolution of smartphone, a preliminary analysis is performed with the arithmetic, geometric and exponential rates of growth per each vital characteristic *i* under study (i=1, …, n).

Let

$FMT_{i,\,2018}$= level of technical characteristic *i* in 2018

$FMT_{i,\,2008}$= level of technical characteristic *i* in 2008

- If the development of technical characteristic *i* (i=1, …, n) in smartphone is assumed to be of *arithmetic type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} + FMT_{i,2008}(r_{art} \cdot t)$$
$$FMT_{i,2018} - FMT_{i,2008} = FMT_{i,2008}(r_{art} \cdot t)$$
$$r_{art} = \frac{FMT_{i,2018} - FMT_{i,2008}}{FMT_{i,2008} \cdot t}$$

- If the development of technical characteristic *i*(i=1, …, n) in smartphone is assumed to be of *geometric type*, the rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008} \cdot (1 + r_{geom})^t$$
$$Log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = t \cdot Log \cdot (1 + r_{geom})$$

$$Log\ \frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} = Log \quad \cdot (1 + r_{geom})$$

$$r_{geom} = \frac{\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t} - 1 \quad \cdot$$

- If the development of technical characteristic i (i=1, …, n) in smartphone is of *exponential type*, the exponential rate of growth is given by:

$$FMT_{i,2018} = FMT_{i,2008}\, e^{rexp_{i} t}$$

$$\frac{FMT_{i,2018}}{FMT_{i,2008}} = e^{rexp_{i} \quad t}$$

$$log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right) = r_{exp_{i}} t$$

$r_{exp_{i}} = \frac{log\left(\frac{FMT_{i,2018}}{FMT_{i,2008}}\right)}{t}$ = rate of exponential growth of technological characteristic *i*. In order to operationalize the approach of hedonic pricing to analyze the drivers of the evolution of smartphone technology, this study considers a log-log model of hedonic pricing, in which smartphone prices are regressed with respect to technological characteristics. The specification of *log-log* model (considering data in natural logarithms) is the following equation:

$$log\ P_{smartp\ hone} = \alpha_0 + \alpha_1 log\ Display\ in\ inch \quad + \cdots + \alpha_i log\ Camera\ (megapixel) + \cdots + \alpha_n logRAM\ Gb \qquad (1)$$

a_0= constant

a_i= coefficient of regression (*i=1, …, n*)

A *t*-test is performed for each coefficient in the hedonic price equation. Standardized values of the coefficients of regression a_i provide information about the most important technological trajectories driving the technological progress of a given product over time. This study also applies the multiple regression analysis of model (1) using the stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100). Moreover, in order to check the generalizability of results, the study applies the hierarchical regression, considering a linear model similar to Eq. [1], to show if additional variables of interest explain a statistically significant amount of variance in dependent variable (Price of smartphone), after accounting for all other variables. This technique determines whether added variables show a significant improvement in R^2 (the proportion of explained variance in dependent variable by the model).

Logical models of hierarchical regression here are:

- Model 1 includes as explanatory variables, technical characteristics of smartphone that interact with visual perception of adopters, such as display resolution in pixels and camera in megapixels.
- Model 2 includes, in addition to model 1, a variable measuring the technical characteristic of storage and functionality of smartphone: RAM in Gb
- Model 3 includes, in addition to model 2, a variable about the long life of battery in mAh that allows a longer temporal utilization of smartphones for fulfil needs of adopters.

Hierarchical regression calculates ΔR^2 and ΔF to determine if model 2 and model 3 are better than model 1. The equations of regression analyses here are estimated using the Ordinary Least Squares method. Statistical analyses are performed with the Software IBM SPSS Statistics version 21.

5. Results

Table 2 shows descriptive statistics, using a natural logarithmic scale. In general, variables in natural logarithm have normal distribution, except technical characteristics of Display in inches, 1^{st} Camera Mpx, Processor and Memory. For these variables, if values not transformed in natural logarithmic scale have normal distribution, they are used in statistical analyses, otherwise variables not having normal distribution are not considered in statistical analyses. The normality of distribution of FMT is important to apply correct parametric analyses and reduce distortions and misleading results. Table 3 shows bivariate correlation between variables having normal distribution.

Table 2. *Descriptive statistics of technical characteristics of smartphone*

	log Price in Euros	*log* Display in inches	*log* Resolution display pixels	*log* 1^{st} Camera megapixel	*log* 2^{nd} Camera megapixel	*log* Processor GHz	*log* Memory Gb	*log* RAM Gb	*log* Battery mAh
N Valid	735	733	733	724	624	673	716	656	727
Missing	0	2	2	11	111	62	19	79	8
Mean	5.206	1.551	13.735	2.303	1.416	0.414	2.710	0.717	7.792
Std. Deviation	0.647	0.260	1.157	0.786	1.073	0.438	1.443	0.742	0.381
Skewness	-.034	-2.018	-1.094	-1.528	-1.111	-2.597	-1.669	-.750	-.783
Std. Error of Skewness	.090	.090	.090	.091	.098	.094	.091	.095	.091
Kurtosis	.379	4.125	1.174	4.507	.780	12.780	4.083	2.346	.092
Std. Error of Kurtosis	.180	.180	.180	.181	.195	.188	.182	.191	.181
Minimum	3.07	.372	9.704	-1.204	-1.204	-2.283	-5.298	-3.219	6.620
Maximum	7.44	1.917	15.931	4.220	3.332	1.030	5.545	3.466	8.517

Table 3 shows that the highest bivariate correlation is given by: *log* price and *log* resolution display in px (r=0.66, p-value=0.01), *log* price and processor GHz (r=0.61, p-value=0.01), *log* price and *log* RAM Gb (r=0.58, p-value=0.01), *log* price and display in inches (r=0.56, p-value=0.01). Coefficient of correlation is lower between *log* price and *log* battery MAh (r=0.51, p-value=0.01), *log* price and *log* 2^{nd} Camera Mpx (r=0.41, p-value=0.01).

Table 3. *Correlations*

		log Price Euro	*log* Resolution display pixels	*log* 2^{nd} Camera megapixel	*log* RAM Gb	*log* Battery mAh	Display in inches	Processor in Ghz
log Price Euro	Pearson Correlation	1						
	Sig. (2-tailed)							
	N	735						
log Resolution Display pixels	Pearson Correlation	.655**	1					
	Sig. (2-tailed)	.001						
	N	733	733					
log 2^{nd} Camera megapixels	Pearson Correlation	.408**	.673**	1				
	Sig. (2-tailed)	.001	.001					
	N	624	624	624				
log RAM Gb	Pearson Correlation	.575**	.714**	.736**	1			
	Sig. (2-tailed)	.001	.001	.001				
	N	656	656	617	656			
log Battery MAh	Pearson Correlation	.509**	.849**	.689**	.683**	1		
	Sig. (2-tailed)	.001	.001	.001	.001			
	N	727	727	624	654	727		
Display in inches	Pearson Correlation	.564**	.905**	.697**	.643**	.914**	1	
	Sig. (2-tailed)	.001	.001	.001	.001	.001		
	N	733	733	624	656	727	733	
Processor GHz	Pearson Correlation	.609**	.838**	.562**	.781**	.669**	.711**	1
	Sig. (2-tailed)	.001	.001	.001	.001	.001	.001	
	N	673	673	609	638	670	673	673

Note: ** Correlation is significant at the 0.01 level (2-tailed).

Table 4 shows the arithmetic, geometric and exponential rates of growth of the technical characteristics of smartphone technology. Although differences of magnitude between these types of growth, the ranking of important technical characteristics having higher evolution is similar from the highest to lowest value between these different models. Table 4 shows, in decreasing order, that the technical characteristics in smartphone technology that have had the highest exponential growth r_{exp} from 2008 to 2018 are respectively: Gb of memory=1.02; Gb of RAM=0.67, resolution display in px=0.62; Mpx of main camera= 0.54, Mpx of second camera=0.45. The lowest rates are for mAh of battery=0.19 and inches of display=0.16.

The first technical characteristic that, according to these rates in table 4, has had higher growth is memory Gb and RAM because of increasing needof smartphone to have large memory and RAM for allowing continuous updates of software applications and greater functionality (in fact, apps are more and more symbiotic technologies within complex systems of smartphones; Coccia, 2018h). The accelerated improvement of other technical characteristics (i.e., higher resolution of display and Mpx of cameras) is associated with visual perception of adopters that increase their satisfaction with better displays, images and videos (cf., Bhalla & Proffitt, 1999; Iriki *et al.,* 1996; Leutgeb *et al.,* 2005).

Table 4. *Rates of exponential, geometric and arithmetic growth in technical characteristics of smartphone technology from 2008 to 2018*

Rates of growth	Memory Gb	RAM Gb	Resolution Display Pixels	1st Camera Megapixels	2nd Camera Megapixels	Processor GHz	Battery mAh	Display in inches
r exponential	1.015	0.668	0.623	0.542	0.454	0.331	0.190	0.155
r geometric	1.759	0.951	0.864	0.720	0.574	0.393	0.209	0.167
r arithmetic	2559.900	79.900	50.525	22.567	9.233	2.645	0.567	0.369

Table 5 suggests some symbols to indicate the intensity of growth of technological trajectories, measured with exponential rates of growth as illustrated in table 4. Hence, for instance, the evolutionary pathways of display in inches is \ = steady-state growth, main camera=+ (growth), and memory in Gb= ! (high development).

Table 5. *Scale for rating the acceleration of technological trajectories within complex systems of technology*

Symbol	Description	Measure of the growth of technical characteristics with r_{exp}
!	High development of technological trajectory	$r_{exp}>1$
+	Growth of technological trajectory	$0.5 \le r_{exp} \le 1$
/	Steady-state technological trajectory	$r_{exp} < 0.5$

Table 6. *Estimated relationship for the evolution of smartphone technology (log-log model)*

Dependent variable: *log* Price

Smartphone	*Unstandardized Coefficient*	*Standardized Coefficient*	*t-test*
Constant. α (St. Err.)	1.41 (0.80)		1.77
Coefficient *log* Resolution Display in pixels (St. Err.)	0.44*** (0.04)	0.58	11.62
Coefficient *log* 2nd Camera megapixel (St. Err.)	−0.05* (0.03)	−0.1	−2.06
Coefficient *log* RAM Gb (St. Err.)	0.27*** (0.05)	0.30	2.50
Coefficient *log* Battery mAh (St. Err.)	−0.32*** (0.1)	−0.15	−3.23
R^2 adj. adj. *(St. Err. of the Estimate)*	0.44 (0.43)		
F *(sign.)*	124.16 (0.001)		

Note: *** *p-value*< .001 ** *p-value*< .010 * *p-value*< .050

Table 6 shows that the evolutionary pathways of smartphone technology is, in average, driven by resolution of display in pixels and performance of RAM in Gb as suggested by standardized coefficients of regression. Moreover, the OLS estimation of model in table 6 indicates that a 1% higher level of quality in Display resolution increases the expected price of smartphone by about 0.44% (*p*-value<.001), whereas a 1% higher level of Gb in RAM increases the expected price of smartphone by about 0.27% (*p*-value<.001). Using the multiple regression analysis with stepwise method (Criteria: Probability-of-*F*-to-enter <= .050, Probability-of-*F*-to-remove >= .100), R^2 adjusted of the model indicates that about 42% of the variation in price can be attributed (linearly) to the resolution of display in px as predictor. Table 7 shows that models with other variables entered increase the goodness of fit of about 2%, achieving 44% with four predictors (cf., model 4d. in Tab. 7).

Table 7. *Model summary with stepwise method*

Model	*Adjusted R Square (std. error of the estimate)*	*F*	*Sign.*
1 a.	0.415 (0.438)	436.27	0.001
2 b.	0.427 (0.433)	230.86	0.001
3 c.	0.441 (0.428)	163.27	0.001
4 d.	0.444 (0.427)	124.16	0.001

Note: Dependent variable is *log* price in euros.
a. Predictors: (Constant), *log* resolution display in px
b. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb
c. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh
d. Predictors: (Constant), *log* resolution display in px, *log* RAM in Gb, *log* Battery in mAh, *log* second camera in Mpx

Table 8. *Hierarchical regression analysis of predictors of smartphone prices*

	Model 1	*Model 2*	*Model 3*
Constant λ_0	−1.94***	−0.61	1.41
(St. Err.)	(0.43)	(0.50)	(0.80)
log (Resolution Display in Pixels)			
Coefficient λ_1	0.52***	0.41***	0.44***
(St. Err.)	(0.03)	(0.04)	(0.04)
log 2nd camera in Megapixels			
Coefficient λ_2	−0.02	−0.08***	−0.05*
(St. Err.)	(0.02)	(0.03)	(0.03)
log RAM Gb			
Coefficient λ_3		0.24***	0.27***
(St. Err.)		(0.05)	(0.05)
log Battery mAh			
Coefficient λ_4			−0.32***
(St. Err.)			(0.10
F	218.56	159.61	124.16
Sig.	0.001	0.001	0.001
R^2 *adj.*	0.41	0.436	0.444
(St. Err. of the Estimate)	(0.44)	(0.43)	(0.43)
ΔR^2	0.41	0.023	0.009
ΔF	218.56***	24.78***	10.43***

Note: Dependent variable: *Log* Price. *** = *p-value*< .001 ** = *p-value*< .010 * = *p-value*< .050

Models of hierarchical regression in table 8 show that Model 1 of the hierarchical ordering including technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx), entered together, contribute significantly: R^2 adjusted of the model indicates that about 41% of the variation in price can be attributed (linearly) to these technical characteristics. Other variables, such as main camera, are not included because they have not normal distribution. At next stage, in model 2, the technical characteristic of storage and functionality of smartphones given by RAM in Gb explains about 2.3% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters, which is a significant amount (*p*-value<0.001). At the next stage, in model 3, the long life of battery in mAh explains about 1% of the variance accuracy scores over and above the technical characteristics associated with visual perception of adopters and the technical characteristic of storage and functionality of smartphones given by RAM in Gb (*p*-value<0.001).

Table 9 shows descriptive statistics of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. The maximum value indicates the highest level achieved by technical characteristics in 2018.

Table 9. *Descriptive statistics of the evolutionary stepwise improvements of technical characteristics in smartphone technology from 2008 to 2018*

Technical characteristics	N	Minimum	Maximum	Mean	Std. Deviation
Display in inches	55	1.45	6.80	4.44	1.49
Resolution Display total pixels	33	16384.00	8294400.00	1411271.03	1845077.45
1st Camera megapixels	38	0.30	68.00	18.50	13.72
2nd Camera megapixels	25	0.30	28.00	7.85	8.25
Processor GHz	29	0.10	2.80	1.45	0.81
Memory Gb	30	0.01	256.00	17.25	52.02
RAM Gb	15	0.04	32.00	4.96	8.39
Battery MAh	123	750.00	5000.00	2411.87	931.22

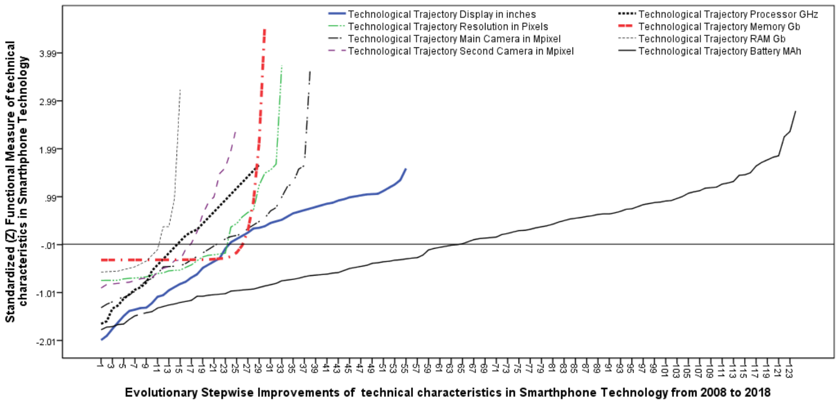

Figure 1. *Technological trajectories of the evolution of smartphone technology from 2008 to 2018*

Figure 1 shows the representation of technological trajectories of the evolutionary improvements of technical characteristics in smartphone technology from 2008 to 2018. Figure 1 reveals two patterns of technological evolution of these characteristics in smartphone technology:

- *Arithmetic* growth of technological trajectories is for the technological characteristics of battery in mAh, display in inches, and processor in GHz.
- *Exponential* growth of technological trajectories is for the technological characteristics of RAM in Gb, 1st and 2nd camera in Mpx, memory in Gb and resolution in total pixels.

Therefore, representation of the evolution of technological trajectories from 2008 to 2018 in Figure 1 suggests that smartphone technology is driven mainly by technological characteristics associate with visual perception of adopters (high definition of display and camera), storage (memory) and functionality with RAM in Gb.

Table 10. *Estimated relationships of evolutionary improvements of technical characteristics in smartphone technology*

Models	*Mod. 1 linear*	*Mod. 2 linear*	*Mod. 3 linear*	*Mod. 4 Exp*	*Mod. 5 Exp*	*Mod. 6 Exp*	*Mod. 7 linear*	*Mod.8 linear*
Constant β_0	1.88***	792.52***	0.02	2.35***	0.48***	10.27***	–4.33***	–3.04***
(St. Err.)	(0.08)	(26.95)	(0.01)	(0.37)	(0.04)	(0.14)	(0.36)	(0.14)
Display in inches *Coefficientβ_1*	0.09***							
(St. Err.)	(0.002)							
Battery mAh *Coefficientβ_2*		25.73***						
(St. Err.)		(0.37)						
Processor Ghz *Coefficientβ_3*			0.10***					
(St. Err.)			(0.001)					
1st Camera Mpx *Coefficientβ_4*				0.09***				
(St. Err.)				(0.007)				
2nd Camera Mpx *Coefficientβ_5*					0.17***			
(St. Err.)					(0.005)			
*log*Resolution px *Coefficientβ_6*						0.014***		
(St. Err.)						(0.001)		
*log*Memory Gb *Coefficientβ_7*							0.26***	
(St. Err.)							(0.02)	
*log*RAM Gb *Coefficientβ_8*								0.42***
(St. Err.)								(0.02)
F	1420.28	4766.17	14001.71	149.99	1176.20	391.32	159.38	772.84
Sig.	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
R^2 adj.	0.96	0.98	0.998	0.80	0.98	0.92	0.85	0.98
(St. Err. of the Estimate)	(0.29)	(147.13)	(0.04)	(0.48)	(0.18)	(0.04)	(0.97)	(0.25)

Note: Dependent variable: temporal steps from 2008 to 2018; px is acronyms of pixel. *** = *p-value*< .001 ** = *p-value*< .010 * = *p-value*< .050

Table 10 shows the parametric estimates of linear or exponential models of the technological evolution of technical characteristics in smartphone technology. Results are consistent with previous statistical analyses. The R^2 values are nevertheless very high. Thus in majority of cases models explain more than 90% variance in the data.

6. Discussionand concluding observations

This article proposes a hedonic price method for the analysis of the most important technical characteristics supporting the evolution of smartphone technology. In particular, the approach here is based on a simple assumption that technologies are complex systems based on interrelated sub-systems of technologies. The approach is formalized with a simple *log-log model of hedonic pricing*, which is useful to be generalized in order to predict which technical characteristics within complex systems of technology (e.g., smartphone) are likeliest to evolve rapidly. This approach seems also to be appropriate to detect evolutionary pathways of new technology that may sustain competitive advantage of firms and fulfil needs of adopters in markets.

The results here are that evolutionary pathways of smartphone technology are, in average, driven by display resolution in pixel and performance of RAM in Gb as suggested by standardized coefficients of regression.

In particular, hierarchical regression suggests that technical characteristics of smartphone that interact with visual perception of adopters (resolution display in pixels and second camera in Mpx) contribute significantly to technological evolution of this ICT. This result is represented in figure 1 that shows *exponentialgrowth* of the technological characteristics of RAM in Gb, 1st and 2nd camera in Mpx, memory in Gb and resolution in total pixels, whereas other technical characteristics have arithmetic pathways of growth.

This result of smartphone technology is consistent with the market of digital cameras that shows how the evolutionary pathway of resolution from 1998 to 2001 is increased from around 0.5 to more than 1.5 megapixels (Carranza, 2010). This finding indicates that the long-run evolution of smartphone technology depends on the behavior and evolution of associated technologies (cf., Sahal, 1981, Coccia, 2017b). In fact, the evolution of smartphone technology, as a complex system, is driven by a coevolution of innovations in digital cameras and other technologies, such as resolution HD, full HD, Quad HD or 2K, 4K or Ultra HD as well as new technology for displays, e.g., LCD, OLED, AMOLED, Super AMOLED, TFT-LCD, Retina, etc. As a matter of fact, evolutionary pathways of smartphone technology are due to the effects of cumulative learning from digital technology (cf., Watanabe *et al.,* 2012). In particular, learning effects, based on learning by doing and learning by using, are fostering the assimilation of new technology in smartphone devices (Cohen & Levinthal, 1990). Sahal (1981, p.82, original italics) argues that: "the role of learning in the *evolution* of a technique has profound implications for its *diffusion* as well". Williams *et al.,* (2000) suggest: "a concept of domestication which tames assimilated spillover technology for a whole institutional system in a co-evolutionary way" (as quoted by Watanabe *et al.,* 2012, p.1293). Watanabe *et al.,* (2012, pp.1293-1294) claim that mobile phones can attract a vast spectrum of adopters by incorporating "super-functionality, and…. users are transformed into explorers in search of further exciting stories based on their own initiative and this then thrills them with gratification of such exploration".In general, this study shows that the evolution of technology is driven by the interaction between smartphone technology and its subsystem components, e.g., displays, camera, etc. that drive the evolutionary pathways of these complex systems of technology and technological diversification over time and space (cf., Coccia, 2017b). The finding of this study could aid technology policy and management of technology to design best practices for supporting the development of technological trajectories with faster rates of growth. The hedonic price method applied here for assessing technological evolution is useful for: "products that can be represented as sets of characteristics and for which both characteristics values and corresponding prices are known for a sufficiently large number of models" (Saviotti, 1985, p.314-315). In addition, within competitive markets, well informed adopters are available to pay a given price for a product only if the levels of characteristics supplied satisfy their requirements. The analysis of the evolution of technological characteristics and pricing behavior of different products within smartphone industry can therefore serve to compare the performance of different technologies and provide information of its technical progress and evolutionary pathways.

However, drawbacks of the approach here to analysis of the evolution of technology are that hedonic pricing function cannot, in general, be rigorously derived from theories of consumer demand or from the production function. Its theoretical status is still not clear (cf., Saviotti, 1985, Triplett, 1985). In short, hedonic pricing applied to technological evolution needs improvements in the theoretical framework and its empirical evidence. Some of the methodological issues (e.g., choice of variables, data collection, etc.) are common to all methods of technology analysis, while others are specific to the hedonic price method. For instance, a price-technological characteristics relationship should only be applicable to a homogeneous market (Muellbauer, 1974, p.988). Saviotti (1985, p.334, original emphasis) also argues that: "the hedonic price method cannot be used in an 'unskilled' way to measure changes in technology". Of course, this approach requires an accurate knowledge of the technology under study.

To conclude, the proposed approach here keeps its validity in explaining specific technological characteristics supporting the evolutionary pathways of a given technology, such as smartphone. In particular, this study constitutes an initial significant step in the application of hedonic pricing method to study the evolution of technology considering the interaction between technologies in complex systems to predict fruitful technological trajectories. Hence, this study may lay the foundation for development of more sophisticated theoretical frameworks in technology analysis and technological forecasting, using hedonic pricing, to detect and forecast the evolutionary technological trajectories of a given complex system of technology. Nevertheless, the identification of a comprehensive method for detecting critical pathways of the evolution of technology that depends on the behavior of the other technologies is a non-trivial exercise, because manifold factors are not equal over time and space as well as between different technologies. Wright (1997, p.1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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Notes

[i] For studies about the role of science, technology, sources of innovation and knowledge in society, see also, Calabrese *et al.,* 2005; Cariola & Coccia, 2004; Cavallo *et al.,* 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.,* 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

[ii] The display resolution is usually quoted as width × height, with the units in pixels: for example, "1024 × 768" means the width is 1024 pixels and the height is 768 pixels. Total pixels= 1024 × 768=786,432 pixels.

References

Arthur, B.W. (2009). *The Nature of Technology. What it is and How it Evolves*. Free Press, Simon & Schuster.

Arthur, B.W., & Polak W. (2006). The evolution of technology within a simple computer model, *Complexity*, 11(5), 23-31. doi. 10.1002/cplx.20130

Bellitto, M., & Coccia, M. (2018). Interrelationships between Violent crime, demographic and socioeconomic factors: A preliminary analysis between Central-Northern European countries and Mediterranean countries, *Journal of Economic and Social Thought*, 5(3), 230-246.

Bhalla, M., & Proffitt D.R. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology. Human Perception and Performance*, 25(4), 1076-1096. doi. 10.1037/0096-1523.25.4.1076

Calabrese, G., Coccia M., & Rolfo S. (2005). Strategy and market management of new product development: evidence from Italian SMEs, *International Journal of Product Development*, 2(1-2), 170-189. doi. 10.1504/IJPD.2005.006675

Carranza, J.E. (2010). Product innovation and adoption in market equilibrium: The case of digital cameras, *International Journal of Industrial Organization*, 28(6), 604-618. doi. 10.1016/j.ijindorg.2010.02.003

Coccia, M. (2001). Satisfaction, work involvement and R&D performance. *International Journal of Human Resources Development and Management*, 1(2-3-4), 268-282. doi. 10.1504/IJHRDM.2001.001010

Coccia, M. (2003). Metrics of R&D performance and management of public research institute. *Proceedings of IEEE- IEMC 03*, Piscataway, pp.231-236.

Coccia, M. (2004). Spatial metrics of the technological transfer: analysis and strategic management. *Technology Analysis & Strategic Management*, 16(1), 31-52. doi. 10.1080/0953732032000175490

Coccia, M. (2005). Countrymetrics: valutazione della performance economica e tecnologica dei paesi e posizionamento dell'Italia, *Rivista Internazionale di Scienze Sociali*, CXIII(3), 377-412.

Coccia, M. (2005a). Metrics to measure the technology transfer absorption: analysis of the relationship between institutes and adopters in northern Italy. *International Journal of Technology Transfer and Commercialization*, 4(4), 462-486. doi. 10.1504/IJTTC.2005.006699

Coccia, M. (2005b). Technometrics: Origins, historical evolution and new direction, *Technological Forecasting & Social Change*, 72(8), 944-979. doi. 10.1016/j.techfore.2005.05.011

Coccia, M. (2005c). Economics of scientific research: origins, nature and structure, *Proceedings of Economic Society of Australia*.

Coccia, M. (2006). Classifications of innovations: survey and future directions. *Working Paper Ceris del Consiglio Nazionale delle Ricerche*, 8(2), 1-19. [Retrieved from].

Coccia, M. (2006a). Analysis and classification of public research institutes. *World Review of Science, Technology and Sustainable Development*, 3(1), 1-16.

Coccia, M. (2007). A new taxonomy of country performance and risk based on economic and technological indicators, *Journal of Applied Economics*, 10(1), 29-42.

Coccia, M. (2008). Science, funding and economic growth: analysis and science policy implications. *World Review of Science, Technology and Sustainable Development*, 5(1), 1-27. doi. 10.1504/WRSTSD.2008.01781

Coccia, M. (2008a). Spatial mobility of knowledge transfer and absorptive capacity: analysis and measurement of the impact within the geoeconomic space. *The Journal of Technology Transfer*, 33(1), 105-122. doi. 10.1007/s10961-007-9032-4

Coccia, M. (2008b). New organizational behaviour of public research institutions: Lessons learned from Italian case study. *International Journal of Business Innovation and Research*, 2(4), 402–419. doi. 10.1504/IJBIR.2008.018589

Coccia, M. (2009). A new approach for measuring and analyzing patterns of regional economic growth: empirical analysis in Italy. *Italian Journal of Regional Science- Scienze Regionali*, 8(2), 71-95. doi. 10.3280/SCRE2009-002004

Coccia, M. (2009a). Measuring the impact of sustainable technological innovation, *International Journal of Technology Intelligence and Planning*, 5(3), 276-288. doi. 10.1504/IJTIP.2009.026749

Coccia, M. (2010). Public and private R&D investments as complementary inputs for productivity growth. *International Journal of Technology, Policy and Management*, 10(1/2), 73-91. doi. 10.1504/IJTPM.2010.032855

Coccia, M. (2010a). Foresight of technological determinants and primary energy resources of future economic long waves, *International Journal of Foresight and Innovation Policy*, 6(4), 225–232. doi. 10.1504/IJFIP.2010.037468

Coccia, M. (2010b). Energy metrics for driving competitiveness of countries: Energy weakness magnitude, GDP per barrel and barrels per capita. *Energy Policy*, 38(3), 1330-1339. doi. 10.1016/j.enpol.2009.11.011

Coccia, M. (2010c). Spatial patterns of technology transfer and measurement of its friction in the geo-economic space. *International Journal of Technology Transfer and Commercialisation*, 9(3), 255-267. doi. 10.1504/IJTTC.2010.030214

Coccia, M. (2010d). The asymmetric path of economic long waves, *Technological Forecasting & Social Change*, 77(5), 730-738. doi. 10.1016/j.techfore.2010.02.003

Coccia, M. (2010e). Democratization is the driving force for technological and economic change, *Technological Forecasting & Social Change*, 77(2), 248-264. doi. 10.1016/j.techfore.2009.06.007
Coccia, M. (2011). The interaction between public and private R&D expenditure and national productivity. *Prometheus-Critical Studies in Innovation*, 29(2), 121-130. doi. 10.1080/08109028.2011.601079
Coccia, M. (2012). Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia, *Technovation,* 32(6), 370–379. doi. 10.1016/j.technovation.2012.03.005
Coccia, M. (2012a). Evolutionary trajectories of the nanotechnology research across worldwide economic players. *Technology Analysis & Strategic Management*, 24(10), 1029-1050. doi. 10.1080/09537325.2012.705117
Coccia, M. (2012b). Evolutionary growth of knowledge in path-breaking targeted therapies for lung cancer: radical innovations and structure of the new technological paradigm. *International Journal of Behavioural and Healthcare Research*, 3(3-4), 273-290. doi. 10.1504/IJBHR.2012.051406
Coccia, M. (2012c). Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine. *International Journal of Healthcare Technology and Management*, 13(4), 184-197. doi. 10.1504/IJHTM.2012.050616
Coccia, M. (2012d). Driving forces of technological change in medicine: Radical innovations induced by side effects and their impact on society and healthcare. *Technology in Society*, 34(4), 271-283. doi. 10.1016/j.techsoc.2012.06.002
Coccia, M. (2013). What are the likely interactions among innovation, government debt, and employment? Innovation: *The European Journal of Social Science Research*, 26(4), 456–471. doi. 10.1080/13511610.2013.863704
Coccia, M. (2013a). The effect of country wealth on incidence of breast cancer. *Breast Cancer Research and Treatment*, 141(2), 225-229. doi. 10.1007/s10549-013-2683-y
Coccia, M. (2014). Path-breaking target therapies for lung cancer and a far-sighted health policy to support clinical and cost effectiveness. *Health Policy and Technology*, 1(3), 74-82. doi. 10.1016/j.hlpt.2013.09.007
Coccia, M. (2014a). Emerging technological trajectories of tissue engineering and the critical directions in cartilage regenerative medicine. *Int. J. Healthcare Technology and Management*, 14(3), 194-208. doi. 10.1504/IJHTM.2014.064247
Coccia, M. (2014b). Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change. *Technology Analysis & Strategic Management*, 26(7), 733-749, doi. 10.1080/09537325.2014.882501
Coccia, M. (2014c). Driving forces of technological change: The relation between population growth and technological innovation-Analysis of the optimal interaction across countries, *Technological Forecasting & Social Change,* 82(2), 52-65. doi. 10.1016/j.techfore.2013.06.001
Coccia, M. (2014). Socio-cultural origins of the patterns of technological innovation: What is the likely interaction among religious culture, religious plurality and innovation? Towards a theory of socio-cultural drivers of the patterns of technological innovation, *Technology in Society*, 36(1), 13-25. doi. 10.23760/2421-7158.2017.004
Coccia, M. (2014e). Religious culture, democratisation and patterns of technological innovation. *International Journal of Sustainable Society*, 6(4), 397-418. doi. 10.1504/IJSSOC.2014.066771
Coccia, M. (2014f). Structure and organisational behaviour of public research institutions under unstable growth of human resources, *Int. J. Services Technology and Management*, 20(4/5/6), 251–266. doi. 10.1504/IJSTM.2014.068857
Coccia, M. (2014g). Steel market and global trends of leading geo-economic players. International *Journal of Trade and Global Markets*, 7(1), 36-52, doi. 10.1504/IJTGM.2014.058714
Coccia, M. (2015). The Nexus between technological performances of countries and incidence of cancers in society. *Technology in Society*, 42, 61-70. doi. 10.1016/j.techsoc.2015.02.003
Coccia, M. (2015a). Patterns of innovative outputs across climate zones: the geography of innovation, *Prometheus. Critical Studies in Innovation*, 33(2), 165-186. doi. 10.1080/08109028.2015.1095979
Coccia, M. (2015b). General sources of general purpose technologies in complex societies: Theory of global leadership-driven innovation, warfare and human development, *Technology in Society*, 42, 199-226. doi. 10.1016/j.techsoc.2015.05.008
Coccia, M. (2015c). Spatial relation between geo-climate zones and technological outputs to explain the evolution of technology. *Int. J. Transitions and Innovation Systems*, 4(1-2), 5-21. doi. 10.1504/IJTIS.2015.074642
Coccia, M. (2015d). Technological paradigms and trajectories as determinants of the R&D corporate change in drug discovery industry. *International Journal Knowledge and Learning*, 10(1), 29-43. doi. 10.1504/IJKL.2015.071052
Coccia, M. (2016). Asymmetric paths of public debts and of general government deficits across countries within and outside the European monetary unification and economic policy of debt dissolution. *The Journal of Economic Asymmetries*, 15, 17-31. doi. 10.1016/j.jeca.2016.10.003
Coccia, M. (2016a). Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organizational performance in the discovery

process of R&D labs. *Technology Analysis & Strategic Management*, 28(4), 381-395. doi. 10.1080/09537325.2015.1095287
Coccia, M. (2016). Problem-driven innovations in drug discovery: co-evolution of radical innovation with the evolution of problems, *Health Policy and Technology*, 5(2), 143-155. doi. 10.1016/j.hlpt.2016.02.003
Coccia, M. (2016c). The relation between price setting in markets and asymmetries of systems of measurement of goods. *The Journal of Economic Asymmetries*, 14(B), 168-178. doi. 10.1016/j.jeca.2016.06.001
Coccia, M. (2017). The source and nature of general purpose technologies for supporting next K-waves: Global leadership and the case study of the U.S. Navy's Mobile User Objective System, *Technological Forecasting and Social Change*, 116, 331-339. doi. 10.1016/j.techfore.2016.05.019
Coccia, M. (2017a). Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations. *The Journal of Technology Transfer*, doi. 10.1007/s10961-017-9572-1
Coccia, M. (2017b). Varieties of capitalism's theory of innovation and a conceptual integration with leadership-oriented executives: the relation between typologies of executive, technological and socioeconomic performances. *Int. J. Public Sector Performance Management*, 3(2), 148–168. doi. 10.1504/IJPSPM.2017.084672
Coccia, M. (2017c). Sources of disruptive technologies for industrial change. *L'industria –rivista di Economia e Politicaindustriale*, 38(1), 97-120.
Coccia, M. (2017d). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management*, 29(9), 1048-1061. doi. 10.1080/09537325.2016.1268682
Coccia, M. (2017e). A Theory of general causes of violent crime: Homicides, income inequality and deficiencies of the heat hypothesis and of the model of CLASH, *Aggression and Violent Behavior*, 37, 190-200. doi. 10.1016/j.avb.2017.10.005
Coccia, M. (2017f). New directions in measurement of economic growth, development and under development, *Journal of Economics and Political Economy*, 4(4), 382-395.
Coccia, M. (2017g). Disruptive firms and industrial change, *Journal of Economic and Social Thought*, 4(4), 437-450.
Coccia, M. (2017h). The Fishbone diagram to identify, systematize and analyze the sources of general purpose Technologies, *Journal of Social and Administrative Sciences*, 4(4), 291-303.
Coccia, M. (2018). A theory of the general causes of long waves: War, general purpose technologies, and economic change. *Technological Forecasting & Social Change*, 128, 287-295 10.1016/j.techfore.2017.11.013
Coccia, M. (2018a). The relation between terrorism and high population growth, *Journal of Economics and Political Economy*, 5(1), 84-104.
Coccia, M. (2018c). Violent crime driven by income Inequality between countries, *Turkish Economic Review*, 5(1), 33-55.
Coccia, M. (2018d). The origins of the economics of innovation, *Journal of Economic and Social Thought*, 5(1), 9-28.
Coccia, M. (2018e). Theorem of not independence of any technological innovation, *Journal of Economics Bibliography*, 5(1), 29-35.
Coccia, M. (2018e). Theorem of not independence of any technological innovation, *Journal of Social and Administrative Sciences,* 5(1), 15-33.
Coccia, M. (2018f). Classification of innovation considering technological interaction, *Journal of Economics Bibliography*, 5(2), 76-93.
Coccia, M. (2018g). An introduction to the methods od inquiry in social sciences, *Journal of Social and Administrative Sciences,* 5(2), 116-126.
Coccia, M. (2018h). Growth rate of population associated with high terrorism incidents in society, *Journal of EconomicsBibliography*, 5(3), 142-158.
Coccia, M. (2018i). Motivations of scientific research in society, *Journal of Social and Administrative Sciences*, 5(3), 196-216.
Coccia, M. (2018j). Measurement and assessment of the evolution of technology with a simple biological model, *Turkish Economic Review*, 5(3), 263-284.
Coccia, M., & Bellitto, M. (2018). Human progress and its socioeconomic effects in society, *Journal of Economic and Social Thought*, 5(2), 160-178.
Coccia, M., & Igor, M. (2018). Rewards in public administration: a proposed classification, *Journal of Social and Administrative Sciences,* 5(2), 68-80.
Coccia, M., & Bozeman, B. (2016). Allometric models to measure and analyze the evolution of international research collaboration. *Scientometrics*, 108(3), 1065-1084. doi. 10.1007/s11192-016-2027-x
Coccia, M., & Cadario, E. (2014). Organisational (un)learning of public research labs in turbulent context, *International Journal of Innovation and Learning*, 15(2), 115-129. doi. 10.1504/IJIL.2014.059756
Coccia, M., Falavigna, G., & Manello, A. 2015. The impact of hybrid public and market-oriented financing mechanisms on scientific portfolio and performances of public research labs: a scientometric analysis. Scientometrics, 102(1), 151-168. doi. 10.1007/s11192-014-1427-z

Coccia, M., & Finardi, U. (2012). Emerging nanotechnological research for future pathway of biomedicine. *International Journal of Biomedical Nanoscience and Nanotechnology*, 2 (3-4), 299-317. doi. 10.1504/IJBNN.2012.051223

Coccia, M., & Finardi, U. (2013). New technological trajectories of non-thermal plasma technology in medicine. *International Journal of Biomedical Engineering and Technology*, 11(4), 337-356. doi. 10.1504/IJBET.2013.055665

Coccia, M., Finardi, U., & Margon, D. (2012). Current trends in nanotechnology research across worldwide geo-economic players, *The Journal of Technology Transfer*, 37(5), 777-787. doi. 10.1007/s10961-011-9219-6

Coccia, M., & Rolfo, S. (2000). Ricerca pubblica e trasferimento tecnologico: il caso della regione Piemonte. *In* S. Rolfo (ed), *Innovazione e piccole imprese in Piemonte*, Franco Angeli Editore, Milano.

Coccia, M., & Rolfo, S. (2002). Technology transfer analysis in the Italian national research council, Technovation - *The International Journal of Technological Innovation and Entrepreneurship*, 22(5), 291-299. doi. 10.1016/S0166-4972(01)00018-9

Coccia, M., & Rolfo, S. (2007). How research policy changes can affect the organization and productivity of public research institutes, *Journal of Comparative Policy Analysis, Research and Practice*, 9(3) 215-233. doi. 10.1080/13876980701494624

Coccia, M., & Rolfo, S. (2010). New entrepreneurial behaviour of public research organizations: opportunities and threats of technological services supply, *International Journal of Services Technology and Management*, 13(1-2), 134-151. doi. 10.1504/IJSTM.2010.029674

Coccia, M., & Rolfo, S. (2013). Human resource management and organizational behavior of public research institutions, *International Journal of Public Administration*, 36(4), 256-268. doi. 10.1080/01900692.2012.756889

Coccia, M., & Rolfo, S. (2009). Project management in public research organization: Strategic change in complex scenarios. *International Journal of Project Organisation and Management*, 1(3), 235–252. doi. 10.1504/IJPOM.2009.027537

Coccia, M., & Wang, L. (2015). Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy, *Technological Forecasting and Social Change*, 94, 155–169. doi. 10.1016/j.techfore.2014.09.007

Coccia, M., & Wang, L. (2016). Evolution and convergence of the patterns of international scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America*, 113(8), 2057-2061. doi. 10.1073/pnas.1510820113

Cohen, W.M., Levinthal, D.A. (1990). Absorptive capacity: A new perspective on learning and innovation, *Administrative Science Quarterly*, 35(1), 128-152. doi. 10.2307/2393553

Daim, T.U., Byung-Sun Y., Lindenberg, J., Grizzi, R., Estep, J., Oliver, T. (2018). Strategic roadmapping of robotics technologies for the power industry: A multicriteria technology assessment, *Technological Forecasting and Social Change*, 131, 49-66. doi. 10.1016/j.techfore.2017.06.006

Farrell, C.J. (1993). A theory of technological progress, *Technological Forecasting and Social Change*, 44(2), 161-178. doi. 10.1016/0040-1625(93)90025-3

Faust, K. (1990). Early identification of technological advances on the basis of patent data, *Scientometrics*, 19(5-6), 473-480. doi. 10.1007/BF02020708

Ferrari, E., Bollani, L., Coccia, M., Cavallo , E. (2013). Technological Innovations in Agricultural Tractors: Adopters' Behaviour Towards New Technological Trajectories and Future Directions, Working Paper Ceris del Consiglio Nazionale delle Ricerche, 15(5), [Retrieved from].

Gherardi, M., & Rotondo, P. (2016). Measuring logic complexity can guide pattern discovery in empirical systems, *Complexity*, 21(S2), 397-408. doi. 10.1002/cplx.21819

Hall-Bronwyn, H., & Jaffe, A.B. (2018). Measuring science, technology, and innovation: A review. *Annals of Science and Technology Policy*, 2(1), 1-74. doi. 10.1561/110.00000005

Hodgson, G.M., & Knudsen, T. (2006). Why we need a generalized Darwinism, and why generalized Darwinism is not enough. *Journal of Economic Behavior and Organization*, 61(1), 1-19. doi. 10.1016/j.jebo.2005.01.004

Hodgson, G.M., & Knudsen, T., (2008). In search of general evolutionary principles: Why Darwinism is too important to be left to the biologists. *Journal of Bioeconomics*, 10(1), 51- 69. doi. 10.1007/s10818-008-9030-0

Iriki, A., Tanaka, M., Iwamura, Y. (1996). Attention-induced neuronal activity in the monkey somatosensory cortex revealed by pupillometrics. *Neuroscience Research*, 25(2), 173-181. doi. 10.1016/S0168-0102(96)01043-7

Lacohée, H., Wakeford, N., & Pearson, I. (2003). A social history of the mobile telephone with a view of its future, *BT Technology Journal*, 21(3), 203–211. doi. 10.1023/A:1025187821567

Lee, H.P., & Lim, S.P. (2014). Comparative studies of perceived vibration strength for commercial mobile phones. *Applied Ergonomics*, 45(3), 807-810. doi. 10.1016/j.apergo.2013.07.006

Leutgeb, S., Leutgeb, J.K., Barnes, C.A., Moser, E.I., McNaughton, B.L., Moser, M. (2005). Independent codes for spatial and episodic memory in hippocampal neuronal ensembles. *Science*, 309(5734), 619-623. doi. 10.1126/science.1114037

Linstone, H.A. (2004). From information age to molecular age, *Technological Forecasting and Social Change*, 71(1-2), 187-196. doi. 10.1016/j.techfore.2003.09.004

McNerney, J., Farmer, J.D., Redner, S., Trancik, J.E. (2011). Role of design complexity in technology improvement, *Proceedings of the National Academy of Sciences*, 108(22), 9008-9013. doi. 10.1073/pnas.1017298108

Muellbauer, J. (1974). Household production theory, quality and the hedonic technique, *The American Economic Review*, 64(6), 977-994.

Punto, C. (2018). Schede Tecniche Cellulari, [Retrieved from].

Sahal, D. (1981). *Patterns of Technological Innovation*. Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

Saviotti, P. (1985). An approach to the measurement of technology based on the hedonic price method and related methods, *Technological Forecasting & Social Change*, 27(2-3), 309-334. doi. 10.1016/0040-1625(85)90064-2

Simon, H.A. (1962). The architecture of complexity, *Proceeding of the American Philosophical Society*, 106(6), 476-482.

Teece, D.J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management, *Strategic Management Journal*, 18(7), 509-533. doi. 10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Tran, T.A., & Daim T.U. (2008). A taxonomic review of methods and tools applied in technology assessment, *Technological Forecasting and Social Change*, 75(9), 1396-1405. doi. 10.1016/j.techfore.2008.04.004

Triplett, J.E. (1985). Measuring technological change with characteristics-space techniques, *Technological Forecasting & Social Change*, 27(2–3), 283-307. doi. 10.1016/0040-1625(85)90063-0

Triplett, J.E. (2006). *Handbook on Hedonic Indexes and Quality Adjustments in Price Indexes: Special Application to Information Technology Products*, OECD Publishing, Paris, 10.1787/9789264028159-en

Wang, C.C., Sung, H.Y., & Huang, M.H. (2016). Technological evolution seen from the USPC reclassifications, *Scientometrics*, 107(2), 537-553. doi. 10.1007/s11192-016-1851-3

Watanabe, C., Kanno, G., & Tou, Y. (2012). Inside the learning dynamism inducing the resonance between innovation and high-demand consumption: A case of Japan's high-functional mobile phones, *Technological Forecasting & Social Change*, 79, 1292–1311. doi. 10.1016/j.techfore.2012.03.003

Watanabe, C., Moriyama, K., & Shin, J. (2009). Functionality development dynamism in a diffusion trajectory: a case of Japan's mobile phones development, Technol. *Technological Forecasting & Social Change*, 76(6), 737-753. doi. 10.1016/j.techfore.2008.06.001

Williams, R., Slack, R., & Stewart, J. (2000). *Social Learning in Multimedia, Research Center for Social Sciences*, The University of Edinburgh, Edinburgh.

Woods, B. (2018). Smartphone screens explained: display types, resolutions and more, Accessed 18th June, 2018. [Retrieved from].

Wright, G. (1997). Towards a more historical approach to technological change, *The Economic Journal*, 107, 1560-1566. doi. 10.1098/rsif.2013.1190